A NUCLEAR MICROBATTERY FOR MEMS DEVICES

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SUMMARY OF PROGRESS

According to our original proposal, approved by the US DOE NEER program under grant DE-FG07-99ID13781, the present work shall accomplish the following objectives, given the subsequent timelines and budget:

Task	Deliverable	Duration (months)	Approx. Cost (k$)
Obtain radioactive material and incorporate into MEMS device	Design and working prototype for a simple MEMS microbattery	18	135
Incorporate several stable isotopes into MEMS device, activate in fission reactor, and measure potential between MEMS surfaces	Detailed designs, processes, and working models for post-fabrication production of a nuclear microbattery	18	135
Repeat above steps using different device designs in order to assess impact of varying geometry on device efficiency	Detailed assessment of various design options and recommendation for choice of optimal design of nuclear microbattery, including optimal isotope, MEMS design, and integration method	12	90
Integrate one or more above concepts into practical MEMS devices such as actuators	Working models of integrated, on-chip power sources for practical MEMS devices	12	90

We have made the following progress on the tasks laid out in our original proposal:

- **Task 1:** A battery has been fabricated using liquid sources (^{63}Ni), providing approximately 0.7 nW at a voltage of approximately 0.05 V. This task is complete (expenditure of $135k).

- **Task 2:** We are in the process of conducting an experiment where glass beads containing ^{6}Li isotopes are irradiated to yield tritium. The tritium will then be used to "fuel" a microbattery (expenditure of approximately $65k).

- **Task 3:** Parametric studies of design issues are just beginning (expenditure of $0).

- **Task 4:** We have integrated a microbattery into a MEMS oscillator. Only design optimization remains (expenditure approximately $65k).

INTRODUCTION

Microelectromechanical Systems (MEMS) comprise a rapidly expanding research field with potential applications varying from sensors in airbags to more recent optical applications. Depending on the application, these devices often require an on-board power source for remote operation, especially in cases requiring operation for an extended period of time. Previously suggested power sources include fossil fuels and solar energy, but nuclear power sources may provide significant advantages for certain applications. Hence, the objective of this study is to establish the viability of nuclear sources (beta and alpha particles) for powering realistic MEMS devices. This approach has previously been used to make large-scale batteries and has the advantage that very high voltages at low power are easily generated.

For example, a common method of actuation of surface micromachines is the use of electrostatic forces between microscopic parallel plates. Such actuation techniques require voltages on the order of 50 to 100 V for useful plate movements of tens of microns. Although these voltages are high, power in the range of only nanowatts to microwatts is needed to run surface micromachines. Voltage sources that produce voltages in this range are too large and negate the advantage of making electromechanical systems at the microscale. For realizing truly autonomous microscale electro-mechanical systems one needs to make integrated microbatteries on the same substrate as the micro-machines. Although several groups have tried to fabricate microbatteries using on-chip liquid-state or solid-state electrochemical cells, they typically only produce a few volts. Integration of transforming circuits to realize high voltages requires inefficient energy conversion and chip area loss. Hence, integration of direct-charging nuclear batteries that produce high voltages with surface micromachined MEMS devices has great potential for advancing the value of MEMS devices. Such integration will enable microscale systems to be used for a number of very important applications.

This work explores the viability of several base designs for such power sources, thus demonstrating the feasibility of producing nuclear, on-board power sources for MEMS devices.

ISOTOPE SELECTION

A critical aspect of the creation of microbatteries for MEMS devices is the choice of isotope to be used as a power source. Some requirements for this isotope include safety, reliability, cost, and activity. Since the size of the device is an issue in this particular application, gamma emitters have not been considered because they would require a substantial amount of shielding. Both beta and alpha emitters have been considered, though the alpha emitters have an advantage due to the short range of the alpha particles. This short range should allow increased efficiency and thus provide more design flexibility, assuming that sufficient activity can be achieved. The half-life of the selected isotopes must be high enough so that the useful life of the battery is sufficient for typical applications, and low enough to provide sufficient activity. In addition, the new isotope resulting after decay should be stable, or it should decay without emitting gamma radiation. The isotopes currently used for this work are:

Isotope	Radiation Type	Half-Life	Max Energy [keV]	Average Energy [keV]
^{3}H	Beta	12.3 y	18.6	5.7
^{63}Ni	Beta	100.2 y	66.9	17.4
^{210}Po	Alpha	138.4 d	5304.3	-

Table 1: Isotopes currently used.

A comprehensive literature review and some scoping calculations have been carried out to explore the viability of the nuclear microbattery concept, concluding that the power available from a radioactive source is about 1 mW/Ci typically. Since the power required for MEMS devices ranges from nanowatts to microwatts, a pure source provides more than sufficient activity to power a practical device.

INCORPORATION OF SOURCES INTO THE DEVICE

One of the more challenging tasks in this project is to develop the techniques to incorporate the radioactive source into the MEMS device. First we need to maximize the efficiency in utilizing the energy emitted by the source, while providing an easy, inexpensive and low exposure assembly procedure. Three methods of incorporating radioactive material into the MEMS devices are being studied. These are 1) activation of layers within the MEMS device, 2) addition of liquid radioactive material into fabricated devices, and 3) addition of solid radioactive material into fabricated devices.

In the first approach, the parent material for the radioactive daughter or granddaughter will be manufactured as part of the MEMS device, most likely near the surface of the device. After fabrication of the device, the parent material would be exposed to the radiation field in our TRIGA reactor for a period of time until the desired radiation source strength is achieved. Highly absorbing neutron or charged particle materials would be used to mask other components of the device that are to remain non-radioactive. In addition, the material used for the activation would be chosen such that it has a high activation cross-section, thus maximizing the activation of the "source" and minimizing competing activity produced in surrounding structures.

In the second and third approaches, radioactive sources are introduced into the MEMS device after fabrication. In the case of a liquid source, a reservoir must be created within the device, along with a channel providing access to the reservoir. The reservoir can then be filled, relying on capillary action to create the flow, and the channel can then be sealed off if needed.

In the case of a solid source, the radioactive material will have to be deposited in selected sites on the device. We currently have two approaches to create this type of sources:

- **Electroless Plating of ^{63}Ni:**

Electroless plating is the plating of nickel without the use of electrodes but by chemical reduction. Metallic nickel is produced by the chemical reduction of nickel solutions with hypophosphite within an autocatalytic bath. The plating metal can be deposited in the pure form on to the plated surfaces. The bath is an aqueous solution of nickel salt and contains relatively low concentration of hypophosphite. This type of nickel plating can be used on a large group of metals, such as steel, iron, platinum, silver, nickel, gold, copper, cobalt, palladium and aluminum.

In order to promote the chemical reduction reaction the bath needs to be heated throughout the plating process, to maintain it at a temperature in the range of 90 – 100 °C. At lower temperatures the reaction proceeds slowly and at higher temperatures the bath evaporates. Therefore the boiling temperature of the bath is to be avoided. The important factor influencing the plating process is the pH. The pH needs to be maintained at 4.5 - 6 for plating to occur. A lower pH results in no plating at all.

We have successfully plated gold-coated silicon pieces of dimensions 2 mm by 2 mm, following this procedure. Plating of nickel on gold was observed in about 15 minutes. These solid sources can then be incorporated into a MEMS device.

This technique allows us to micromachine the surfaces to the desired shape with the necessary tolerances handling non-radioactive materials, and then incorporate the required amount of radioactive material in the appropriate locations.

- **^{3}H Microspheres**

We have obtained glass microspheres (25 to 53 µm in diameter) that will emit low energy ^{3}H beta radiation after activation in a reactor. The tritium is obtained by irradiating ^{6}Li glass silicate non-radioactive microspheres in the UW Nuclear Reactor. Using this procedure, we can produce activities of up to 12.8 mCi per gram per hour of irradiation. Then, these radioactive microspheres can be introduced in the MEMS device in the appropriate cavity.

These latter approaches will allow for higher power densities than the direct reactor activation approach, but will provide less flexibility with respect to device design. We continue exploring the tradeoffs of the different options, and will shortly release a feasibility analysis of all these approaches.

SAFETY ASSESSMENT

Since this work involves the use of small amounts of radiation and radioactive materials, it is necessary to comply with current Radiation Protection Standards. The potential health and environmental effects of fabricating, using and disposing of these nuclear micro-batteries have been studied in detail, and are put in perspective by comparing them with the effects of using an ^{241}Am smoke detector[1].

- **Manufacturing Process**

Our analysis demonstrates that the potential radiation exposure to a worker due to the fabrication of these nuclear micro-batteries is well below the limits established by current laws. Our study includes the external as well as the internal exposures due to ingestion or inhalation of the radioactive materials.

The design of the manufacturing process keeps the radiological safety of the workers in mind, while minimizing the costs so that the final price of the micro-batteries is competitive.

- **Use**

MEMS devices, with their integrated nuclear source, will be used in large variety of applications, as sensors, actuators, resonators, etc. As a consequence, we need to demonstrate that their use does not result in any unsafe exposure to radiation. The radioactive material in the device will be encapsulated in a way that the probability of being released into the environment, and being accidentally inhaled or digested is extremely small. However, the analysis has been performed in the worst case scenario, assuming that the full amount of the radioactive material contained by the micro-battery would be accidentally ingested or inhaled.

The external dose associated with these sources is zero, because an alpha particle needs to have an energy of more than 7.5 MeV to penetrate the protective layer of the skin (0.07 mm think), and a ß particle needs to have an energy of more than 70 keV. Since our sources have energies lower than those they are unable to penetrate the skin.

- **Waste Disposal**

Our analysis proves that the environmental impact of disposing of these micro-devices once their useful life has ended, as well as the associated costs are minimal. Since after three half-lives the activity of the isotope has decayed to about 10% of the original activity, the micro-batteries would be below background radiation level in a relatively short time.

JUNCTION TYPE BATTERY

This first concept incorporates a radioactive source into a pn-junction to create a junction-type battery. In this case, the charged particles emitted from the decay of the radioisotope are absorbed by the semiconductor and dissipate most of their energy as ionization of the atoms in the solid, generating Electron-Hole Pairs (EHP). The carriers generated in this fashion are in excess of the number permitted by thermodynamic equilibrium and, if they diffuse to the vicinity of a rectifying junction, they will induce a voltage across the junction.

However, the direct conversion scheme fails as crystalline semiconductor are severely damaged by high-energy particle bombardment. The electron-voltaic effects were studied extensively in the 1950's and it was found that beta particles with energies below 250 keV do not cause substantial damage in silicon. Therefore, liquid ^{63}Ni was selected as the radioactive source for these tests, since its maximum and average energies (66.9 keV and 17.4 keV respectively) are well below the threshold energy where damage is observed in silicon. In addition, its long half-life (100 years) makes it very attractive for remote long-life applications, such as power of spacecraft instrumentation.

Since it is not easy to microfabricate solid radioactive materials (etching and cutting), a liquid source is used instead for our micromachined pn-junction battery. As shown in Figure 1, a number of bulk-etched channels have been micro-machined in our pn-junction. Compared with conventional planar pn-junctions, the three dimensional structure of our device allows for a substantial increase of the junction area, and the micromachined channels can be used to store the

[1] Smoke detectors contain about 1 µCi of ^{241}Am. ^{241}Am emits 5.48 MeV alpha particles with a half-life of 432.5 years.

liquid source. Our pn-junction has 13 micromachined channels and the total junction area is 15.894 mm^2 (about 55.82% more than the planar pn-junction). This can be very important since the current generated by the powered pn-junction, whether it is powered by the light or by a nuclear source, is proportional to the junction area. Figure 2 shows the I-V curve of our pn-junction due only to the interaction of light, as measured by a semiconductor parameter analyzer.

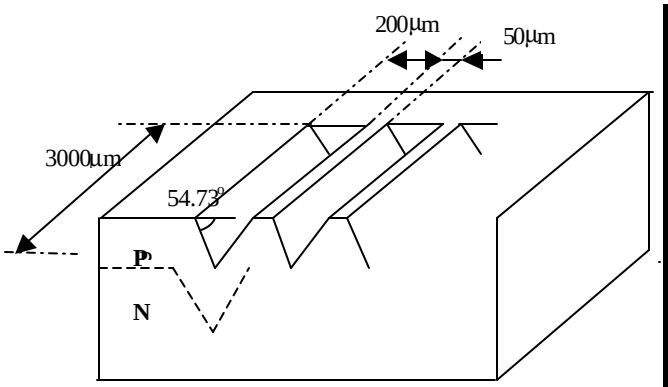


Figure 1. Diagram of a micromachined pn-junction

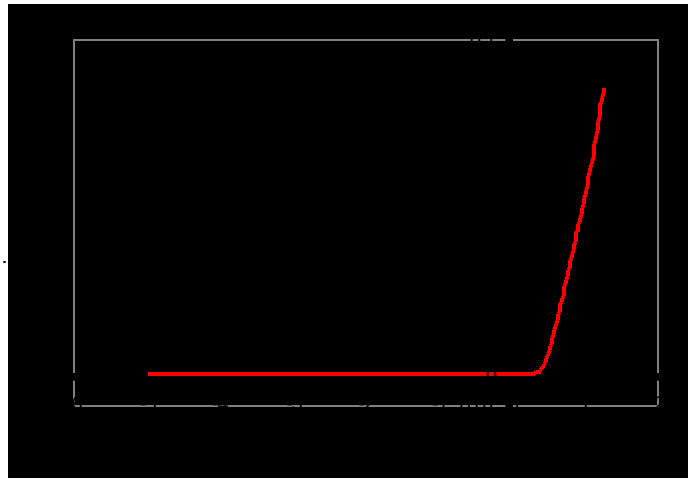


Figure 2. I-V curve of a micromachined pn-junction powered by light.

In order to measure the performance of our three-dimensional pn-junction in the presence of a radioactive source, we use a pipette to place 8 µl of liquid ^{63}Ni source (64 µCi) inside the channels micromachined on top of the pn-junction, and then we cover it with a black box to shield it from the light. The electric circuit used for these experiments is shown in Figure 3.

We obtain the I-V curve by varying the resistance *R* and using the ammeter to measure the current for each resistance value. It is worth noting that the voltage across the pn-juntion is equal to the voltage across the adjustable resistance, which is equal to the product of the resistance *R* and the current flowing through *I*.

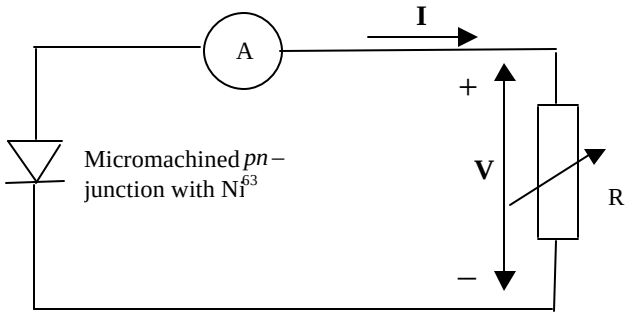


Figure 3: Electric circuit for experiments with micromachined pn-junction and ^{63}Ni.

Figure 4 displays the I-V curves measured at 30 minutes, 2 hours and 16 hours after pouring the radioactive source on the microchannels of the pn-junction. As expected, the degradation of the pn-junction due to the ^{63}Ni is very small. However, to conclusively demonstrate this extreme would require a longer testing time, comparable to the expected life of the nuclear micro-battery.

In Figure 4, we observe that the maximum current generated in the micromachined pn-junction by the ^{63}Ni source, i.e. the short circuit current, is 1.31 nA. In silicon, the generation of one EHP requires about 3.2 eV, even though its energy

gap between the conduction band and covalence band is just 1.12 eV. So the theoretical maximum current generated by 64µCi can be calculated as:

I_{max} = 64 µCi * ($3.7*10^{10}$ dps) * (17.4 keV) / (3.2 eV) * ($1.6*10^{-19}$ C) = $2.06*10^{-9}$ A = 2.06 nA

According to this estimate, the measured current value is 64.07% of the theoretical maximum value. This illustrates the effectiveness of making the boron diffused depth around 40µm during microfabrication, which is approximately the traveling distance of ^{63}Ni beta particles in silicon. Normal pn-junctions, which have ultra shallow junctions (less than 1µm), would result in very low currents since most of the beta particles would stop in the p or in the n regions, instead of the depletion region.

On the other hand, the open circuit voltage is very small, only 53 mV. This is partly due to the large p and n contact resistances. In this particular device, the metal used for the p contact is gold and for the n contact is aluminum alloy, and both the p and n regions are all covered by metal (the open circuit voltage for a normal junction-type battery is in the range of 0.2 to 0.5 V). A very effective way of increasing the open circuit voltage in a junction-type battery is by reducing the contact area.

The maximum power can be approximately estimated by:

$P_{max} = I_s * V_o$ = 1.31 nA * 0.053 V = 0.069 nW

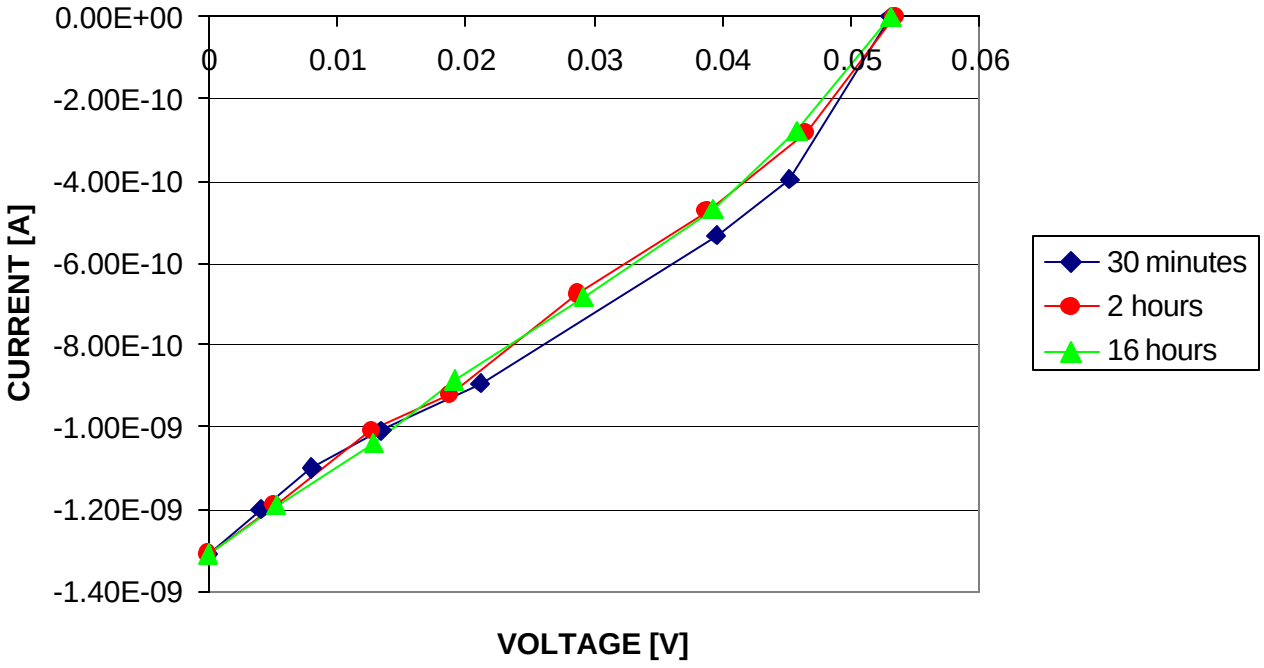


Figure 4: I-V curves for a micromachined pn-junction with ^{63}Ni at different times

Further research on improving device design and its performance is under way and will be released in the near future.

SELF-RECIPROCATING CANTILEVER

This concept involves a more direct use of the charged particles produced by the decay of the radioactive source: the creation of a resonator by inducing movement due to attraction or repulsion resulting from the collection of charged particles. As the charge is collected, the deflection of a cantilever beam increases until it contacts a grounded element,

thus discharging the beam and causing it to return to its original position. This process will repeat as long as the source is active.

This concept has been tested experimentally with positive results. The radioactive source used was ^{63}Ni with an activity of 1mCi. The beam is 5 cm $\times$ 5 mm, made from 60 μm thick copper. A probe tip is glued to the beam to better detect and measure the movement of the beam. Both the source and the beam are mounted on a glass base for electrical insulation. The glass base is clamped so that the beam itself can only move by bending. The measuring scale is a silicon beam with 3μm spaced gridlines so that the movement can be measured with a precision of 1.5μm. A CCD camera connected to a VCR is used to record the movement of the beam and its periodicity.

As the radioactive beta source decays, it emits electrons. The copper beam collects these electrons from the source, and the source itself would become positively charged since it keeps losing electrons; therefore, in the ideal case, there would be an electrostatic force applied on the beam that would bend it. However, in atmospheric conditions, no movement of the beam is observed, due to the ionization of the surrounding air. For that reason, the experiment has been performed under vacuum (typically from 30 mTorr to 50 mTorr), where there is no extraneous ionization and the bending of the beam can be observed. Figure 5 shows a typical experimental result, in which the initial distance is 3.5 mm and the vacuum is 50 mTorr.

In order to understand the behavior of the system we have developed an analytical model for both the charge collection and deflection of the cantilever. The charge collecting process is governed by:

$$dQ = a\,dt - \frac{V}{R}dt$$

where dQ is the amount of charge collected by the beam during a given time dt, α represents the current emitted by the radioactive source, V is the voltage across the source and the beam and R is the effective resistance between them. The second term on the right hand side represents the current leakage arising from the ionization of the air. Since V = Q / C, where C is the capacitance of the beam and the source, the previous equation can be rearranged to obtain:

$$\frac{dQ}{dt} + \frac{1}{RC}Q = a$$

This equation can be readily solved:

$$Q = aRC(1 - e^{-t/RC})$$

In Figure 5 we observe that the beam bends very slowly. Therefore, the electrostatic force on the beam can be taken as balanced by the elastic force from the beam itself. Since the electrostatic force is proportional to Q^2 and the distance between the beam and the source can be taken as a constant, being δ the deflection of the beam, we have:

$$Kd \propto a^2 R^2 C^2 (1 - e^{-t/RC})^2$$

K is the elastic constant of the beam, α can be assumed to be constant since ^{63}Ni has a half life of more than 100 years, R in the experiment is also a constant because the pressure is maintained and no breakdown of the air happened, otherwise the beam will bounce back. C can also be assumed to be constant because it has been observed experimentally that the deflection of the beam is very small compared to the initial distance between the beam and the radioactive source. Therefore:

$$d \propto (1 - e^{-t/RC})^2$$

Figure 5 also compares the deflection measured experimentally with the values obtained analytically according to the discussion shown above, by fitting the value of R. We observe a very good match between them.

This model, however, does not simulate the periodic behavior of this device. Current experiments show a minimum period of about 30 minutes, at which time the electrostatic energy is released as electric current. Further studies are being done in this area, trying to identify the key characteristics of the system in order to be able to design the device with the period and energy release level appropriate for each particular application.

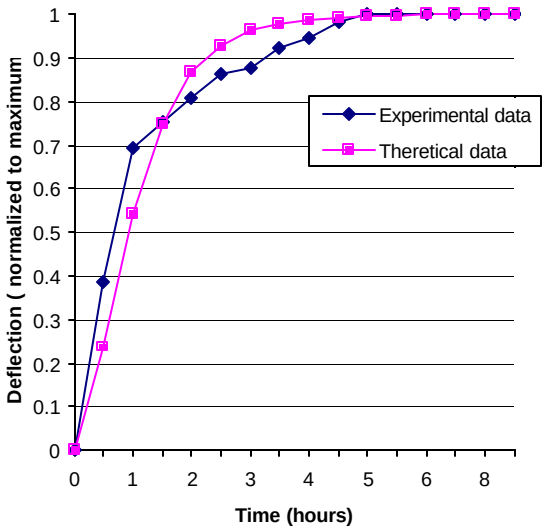
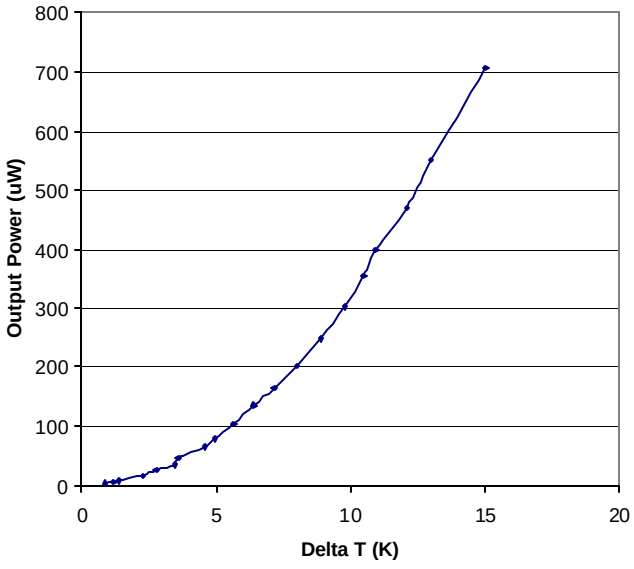


Figure 5: Comparison between the experimental and analytical values for the deflection.

THERMOELECTRIC BATTERY

The third concept of nuclear micro-battery takes advantage of the Seebeck effect, which states that voltage will be generated in a loop of two dissimilar materials if their two junctions are at different temperatures. In the final concept a radioisotope will be used to produce a temperature gradient between the two junctions of a Peltier device (basically a reversed thermocouple), thus creating a voltage. This preliminary experiment though has been designed only to examine the thermoelectric performance of the Peltier device.

Figure 6: Power output vs. temperature gradient generated in the Peltier device.



We use a hot plate to simulate the radioactive source. By varying the heat output from the hot plate, we can evaluate the correlation between the temperature gradient across the Peltier device and the output voltage, generated. The temperatures on the top and the bottom of the Peltier device are measured with arrays of E type thermocouples, which are glued to the surfaces of the Peltier device with high thermal conductivity epoxy. A heat flux probe (episensor) is attached at the top surface to evaluate the heat flux through the device with higher accuracy. All these thermal parameters, plus the voltage and current generated by the Peltier device are the data collected by a Keithley 500A data acquisition system.

Figure 6 shows the relationship between the temperature gradient created by the hot plate and the output power generated by the Peltier device.

While the results are acceptable in the current preliminary case, we recognize that it will be very challenging to obtain such temperature gradients using a radioactive source instead of the hot plate. For that reason, we are currently working in an improved design of the Peltier device to maximize its output for a minimum temperature gradient, and in a smaller size.

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